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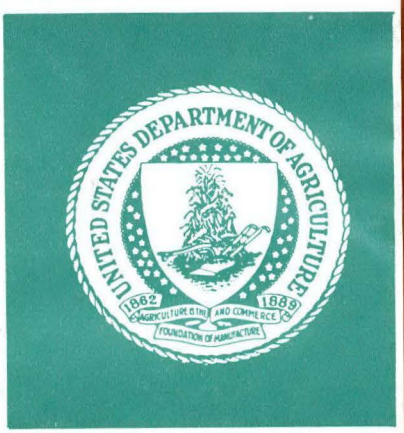

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ECOLOGICAL APPROACHES TO RESTORATION OF DISTURBED WILDERNESS SITES

Prepared for

Intermountain Research Station
USDA Forest Service
Missoula, Montana

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1. INTRODUCTION

Restoration of disturbed wilderness lands is essentially an ecological problem. The loss of vegetation and the alteration of soils in a disturbed site results in the local disruption of a natural ecosystem, and the restoration of a disturbed site necessitates the repair of perhaps several ecosystem components. By looking at recreational impacts in wilderness areas within this ecosystem context, there are important implications and insights for both analyzing these problems and achieving their solutions.

An ecosystem approach to restoration requires a holistic view that includes the entire soil-plant system, as well as interactions among plants and between plants and animals. If the nature of the problem and the restoration process are too narrowly perceived, the underlying constraints on getting vegetation to recover on a disturbed site are likely to be ignored. In addition, the long-term sustainability of a revegetated site is doubtful. The most common example of this happening is the perception of restoration as primarily one of replacing lost vegetation, while what has happened below ground, or even at the ground surface, is not addressed. The result is often the lack of establishment or spread of seedlings and transplants.

An ecosystem approach can also help to utilize ecological processes to increase recovery rates and to minimize the amount of effort expended in restoring and managing a disturbed site. If attention is given to the recovery of soil biota and physical properties, there may be no need for expensive and labor intensive treatments like fertilizer and mulches; and determining what plant characteristics are most critical for plant establishment increases the probability of selecting successful species in a restoration program.

This chapter discusses a variety of ecological processes that have direct bearing on restoration practices in wilderness areas. In the course of this discussion, a strong effort is made to tie these processes to previous restoration projects or to show how they can be

applied to ongoing and future ones. A general emphasis on montane to alpine ecosystems in western North America is used for several reasons: (1) restricting the ecological breadth of the discussion makes it more usable in real situations; (2) a great deal of recreational impacts and much of the previous restoration work in wilderness areas has taken place in these ecosystems; and (3) the author's familiarity with mountain environments allows for a more substantial treatment in applying ecological principles to wilderness restoration. There is, however, some generality to this discussion, in that the ecological processes treated here are common to most ecosystems, even if specific ecosystem characteristics may be different in other areas.

The basic topics of this chapter reflect ecosystem components appropriate to restoring recreationally disturbed sites in wilderness areas. Soil, plant, and ecosystem level processes are dealt with separately, although it is important to keep in mind the interconnections between these components. In addition to these topics, there is also an ecological analysis of several commonly used restoration methods.

2. SOIL PROCESSES

A consideration of soil processes is fundamental to restoring disturbed land, because more often than not soil properties have been altered along with changes to vegetation (Cole 1987). It is pointless to undertake expensive revegetation efforts if soil conditions are no longer suitable for supporting plants at a disturbed site. Soils provide plants with water and mineral nutrients, which are absolutely necessary for plant growth and survival. It is important, then, to determine what physical and biological characteristics of soils have been altered in impacted areas and what consequences these alterations have for water and nutrient availability to plants. By understanding how soils have been damaged, one can better determine what measures need to be taken to restore them to their original conditions.

2.1 Physical factors: soil texture, structure, and horizons

Soils are complex associations of mineral and organic matter, air, and water modified by the activity of plant roots, microorganisms, invertebrates, and mammals. Two important physical properties of soils are texture, which describes the sizes of soil particles, and structure, which describes how soil particles are aggregated (Brady 1974). Soil horizons are different layers of soil with distinct characteristics that are a product of the kind and extent of soil development, including the accumulation of litter. All of these soil physical factors influence the availability of water and nutrients for plants.

Texture (the relative proportion of sand, silt, and clay particles) is a major basis for variation among soils. Soils with different textures have very different drainage and fertility characterstics. Sandy soils are well drained but are usually low in fertility (especially nitrogen), while loamy soils (a more equal mixture of sand, silt, and clay particles) tend to have intermediate but favorable water balance and are usually relatively fertile. Clayey soils are poorly drained, but can be quite variable in their fertility. In general, soils in mountain wilderness areas are sandy to loamy and often are very gravelly. Clayey soils are unusual

in high elevation environments where soils are young and poorly developed and have not had sufficient time for the formation of clay minerals. Knowing which textural class the soils of a disturbed site belong to provides insight into the potential productivity of a site and how that level of productivity has been altered by disturbance.

Soil structure, like any physical structure, is a framework with intervening spaces. The soil framework is determined by the aggregation of small particles of mineral or organic matter. The intervening spaces, called pores, are essential to plant growth because they allow oxygen to reach plant roots, let water infiltrate, and provide pathways for roots to grow. Good soil structure for plant growth is characterized by granules and crumb aggregates that result in many large pores, allowing relatively free movement of air and water around the roots.

How soil particles are aggregated to determine soil structure is influenced by a variety of factors, including the nature of the parent material, soil forming processes such as clay and humus synthesis, the presence and movement of soluble salts, and the activity of plant roots and soil biota. Organic matter derived from decaying plant roots and soil microorganisms promotes the formation of soil aggregates. The presence and kind of soil aggregates are important determinants of soil porosity, which in turn affects soil aeration and root growth. The breakdown of soil structure through compaction is one of the main consequences of severe recreational impact in wilderness areas (Marion and Merriam 1985, Monti and Mackintosh 1979). The loss of soil structure and pore space because of compaction can impede root growth and reduce infiltration rates (Cole and Fichtler 1983, Simmons and Pope 1987). Sandy soils without much organic matter tend to have little aggregation, and their large particle size makes them less susceptible to soil compaction. Highly organic soils (e.g. mucks and peats occuring in wet meadows) and clays are much more vulnerable to compaction, especially when wet.

Soil horizons are typically divided (from the surface downward) into organic (O), A, B, and C horizons. Organic horizons are composed of litter from dead plants that are in various states of decomposition. The A horizons are mineral horizons at or near the surface that have incorporated some organic matter from the overlying O horizons. They are often

referred to as a leaching zone, because they lose minerals and organic compounds as water percolates downward into the B horizons. The B horizons are then the zone of accumulation of these materials and is sometimes referred to as the subsoil. The C horizon is largely unmodified, unconsolidated mineral material below the actual soil. Although the designation of soil horizons is really just a device to help us describe and classify soils, they do provide a systematic way to compare soils and to determine how they have developed. They are also helpful in determining how much soil erosion has occurred when the loss of horizons is evident. By knowing the characteristics of these surface horizons, we can better understand the effects of soil erosion on future plant establishment and growth.

There is considerable variability in soils from montane environments. Soils in subalpine and alpine areas often have little profile development because they are young and poorly developed. Soil processes that lead to horizon development take place at relatively slow rates at high elevations because vegetation is often sparse and slow growing, and soil temperatures are below freezing for much of the year. In forest environments or meadow areas, however, soil development can be quite substantial. In the Cascade and Olympic Mountains of the Pacific Northwest, soil depth in subalpine areas was usually less than 30 cm, but ranged from 2 cm in alpine fell fields to 60 cm in wet meadows (Douglas and Bliss 1977, Kuramoto and Bliss 1970). High montane forest soils in the Olympic Mountains (Fonda and Bliss 1969) and the Big Horn Mountains of Wyoming (Despain 1973) are similarly variable. In soils of similar age, there is usually a close correlation between the depth of the soil and the amount of primary productivity, or vegetative growth, at a particular site. Consequently, meadow soils generally have deeper, better developed soils than more xeric areas nearby.

The thickness of the O horizon depends on the rates of litter fall and decomposition. Coniferous forest floors often have O horizons of 10 cm or more (Despain 1973, Fonda and Bliss 1969), while organic horizons in some alpine areas are non-existent (Douglas 1972). A and B horizons are also variable in thickness and sometimes nonexistent in very poorly developed soils. Since most of the soil organic matter is derived from litter accumulating in the O horizon and also from fine root development in the A horizon, soil organic matter

is proportionately much higher in the upper horizons. Consequently, when soil erosion occurs much of the soil organic matter is lost.

Organic horizons are particularly important to plant growth. They protect the mineral soil from the impact of rain drops; they act as a sponge to soak up rain and melt water, allowing greater infiltration and stemming the erosional effects of surface flow; they contribute organic matter to the underlying A horizons; and they are important sites of nutrient cycling (to be discussed in more detail below).

Organic matter within the mineral soil (i.e. A and B horizons) varies from partially decayed plant roots to highly complex organic molecules, or humus. Organic matter gives soils a variety of qualities beneficial to plant growth. It promotes the formation of soil structure, facilitating infiltration and root growth; it increases the degree of water retention, especially in sandy soils; and it is important for storing and retaining nutrients in the soil. Soils that have lost much of their A horizons through disturbance or erosion are likely to have also lost much of their original organic matter. Another source of organic matter loss is oxidation, which can be increased by turning up the soil (as in scarification of disturbed sites) and exposing the A horizon to the air.

Because montane, subalpine, and alpine soils are so variable, it is difficult to generalize about the effects of recreational impacts on soils. How much attention and what kind of treatments might be necessary to restore them to their original condition is consequently also difficult to predict. In order to assess a disturbed sites previous and current ecological condition, then, it is necessary to characterize the soils. Detailed characterization of soil physical properties and soil profile descriptions are probably unrealistic for most small scale restoration programs in wilderness areas. But digging small soil pits in the disturbed site and also in a similar but undisturbed area can be very informative. Even a superficial examination of soil profiles in the two sites can provide a basic idea of whether it is a sandy, loamy, or clayey soil, how well drained it is, how much organic matter is in the A horizon (the more organic matter the darker the soil color), the severity of compaction, the extent of erosion, and, very importantly, how much loss of the A or organic horizons has occurred.

It is also valuable to get ones hands into the soil for the purpose of becoming acquainted with it. Soil is often ignored because it is not readily visible and takes more effort to examine than aboveground biota, but its importance to plant growth can not be overestimated. For purposes of illustration, it is useful to consider a couple of hypothetical examples of what a general examination of soils might reveal in a recreationally disturbed site.

In the first example, there is no vegetation cover and no litter layer on an impacted campsite occuring under montane to subalpine confirous forest. Digging a small pit about 12 inches deep indicates the soils are very dark, have few roots, and have a platy structure with a fine, flour-like texture to six inches depth. Below six inches, the soil becomes lighter in color and more coarse textured. In a companion, non-impacted site, the upper six to eight inches of soil are again very dark and fine-textured, but they are without the platy structure and are more rich in fine roots. There is also a a layer of litter composed of pine needles, twigs, and some decayed understory herbs. By comparing the disturbed and undisturbed sites, it is evident that the litter layer has been lost in the disturbed site, probably through compaction and erosion. The upper soil horizons are still rich in organic matter, as evident from the fine texture and dark color, but the difference in structure indicates they are somewhat compacted. Most of the impacts on this site are near the soil slurface (i.e., loss of litter, moderate compaction), but the soil is still generally favorable to plant growth, since its high organic content and fine texture holds water well and is likely to be relatively rich in nutrients.

Consider another case in a campsite above treeline on the edge of a turf-like meadow. The sod has been broken down, and the site has a smooth bare soil surface. Digging is particularly difficult because the soil is dense and quite rocky just below the surface. The soil is light in color and is generally rich in clay to about two inches depth, below which it is dominated by broken rock fragments. Unimpacted meadow soil nearby has a three to four inch upper horizon that is quite dark in color and very rich in fine roots (i.e., sod like). Below four inches the soil is more dense and clayey until at about six inches depth it is dominated by rocks like the impacted site. In this example, erosion has removed the

vegeation and most of the A horizon on the impacted site. The clay sub-soil has become quite compacted. Because the soils in this subalpine to alpine area are quite thin (about six inches deep in the undisturbed site), a small amount of erosion has resulted in a relatively large amount of damage to the site's ability to support plants. The impacted soils have likely lost a good proportion of their nutrients because of the loss of the A horizon. Although clay soils hold water well, infiltration rate is likely to be low on the impacted site because of compaction.

Although this is a very brief, and necessarily incomplete, consideration of soil physical factors, it is intended to provide some background for discussing water and nutrient availability in soils. The following paragraphs discuss specific aspects of soil water and nutrient availability in the context of assessing site restoration needs.

2.2 Soil moisture and its availability to plants

Terrestrial plants acquire almost all their moisture through their root systems from the soil, and soil moisture is one of the most important factors limiting plant growth in many environments. The ability of soil to provide moisture to plants depends on the supply of water to the soil, the soil's ability to retain that water, and how easily the plant can extract water from the soil.

In planning the restoration of a site, it is essential to determine soil moisture status. Selection of species and assessing the need for treatments, such as irrigation and mulches, all depend on knowing the likelihood, severity, and timing of drought. Because the factors affecting soil moisture range from regional climate to site specific conditions, analysis of soil moisture conditions must be carried out from a broad perspective.

2.2.1 Climatic control of soil moisture.

Water supply is regionally a function of climate: how much and when precipitation occurs. In general, mountain environments have higher precipitation than nearby lowlands because

of orographic uplifting and cooling of air masses. Nonetheless, drought is an important factor to plant growth in mountain environments, and the timing and severity of drought can be crucial to the success of restoration efforts.

There are very different patterns and amounts of precipitation among and within different mountain ranges (Baker 1944). In the far west, the main source of precipitation is from cyclonic storms moving east from the Pacific Ocean. Since there is less moisture in the air as it progresses eastward, the east slopes of mountains in this region are generally drier than the west slopes. Summer precipitation is very low relative to that in winter, and soils are usually driest in mid- to late summer.

Along the Front Range of the Rocky Mountains in Colorado and New Mexico, there is a different precipitation pattern. The amount of snowfall is considerably less than in the Cascades, Olympics, and Sierra Nevada, and a much greater proportion of the annual precipitation comes from convectional summer storms. Precipitation coming from convectional storms is also much more locally variable than that coming from cyclonic storms. Since these storms usually don't start until late June and early July, soils are driest right after snowmelt before summer storms. From mid- to late-season, moisture tends to be repleneshed near the surface from thundershowers (Ehleringer and Miller 1975). In the northern Rocky Mountains, moisture patterns are mixed, but are probably more like that of the coastal ranges; Despain (1973) concluded that almost all of the soil moisture in montane soils in the Big Horn Mountains of Wyoming was from snowmelt and very little from summer precipitation.

While the generalizations presented here are a guide to evaluating climatic control of moisture availability, it is important to know as specifically as possible what the climatic conditions are in the area where restoration work is to be done. Long-term climatic records from thousands of stations throughout the United States are published by the National Ocean and Atmospheric Administration (NOAA) and can be obtained directly or be found in university librairies (NOAA Climatological Data, National Climate Data Center, Asheville, NC 28801, Tel.No. (704) 259-0682).

2.2.2 Topographic control of soil moisture supply.

Soil moisture on a local scale is in large part a function of topography, which exerts control on patterns of snow accumulation and surface and sub-surface drainage. Since a high proportion of precipitation in mountains falls as snow (especially in the Olympic, Cascade, and Sierra Nevada ranges), areas that accumulate snow or are immediately downslope from late-melting snowbanks tend to have moist soils for much longer periods during the growing season. There is also a general tendancy for ridge crests to have lower soil moisture levels than slope bottoms because of less snow accumulation and drainage of both surface and sub-surface water. Slope aspect can also have a major effect on soil moisture because of the differences in the amount of solar radiation. South facing slopes have longer periods and more direct angles of insolation than north facing slopes. As a result, snow accumulation is lower and evapotranspiration rates are higher on south facing slopes.

2.2.3 Retention of soil water

The ability of soils to retain water depends in large part upon their texture. Sandy soils hold very little water, while clayey and silty soils hold relatively much more. The addition of organic matter to mineral soils, especially sandy ones, can greatly increase moisture holding capacity.

Retention of soil moisture also depends on the rate at which moisture is lost through evapotranspiration, which is the combined loss of atmospheric water through evaporation and plant transpiration. Rates of evapotranspiration are controlled by a variety of factors. Soil evaporation is higher when mineral soils are exposed directly to solar radiation and winds, hence the function of organic horizons and mulches to reduce loss of soil moisture. Once the surface dries, sandy soils tend to have lower evaporation rates than fine- textured soils (loams to clays) (Chapin and Bliss 1988).

Transpirational losses of water are correlated to total plant cover and plant transpiration

rate. Areas with low plant cover have low total transpiration rates, and more drought resistant plants tend to have lower rates (Larcher 1980). Although plant communities at the base of slopes usually have greater moisture supply during early season, the greater plant cover and presence of more mesophytic plants (which transpire at higher rates) can result in lower soil moisture in late season than in areas that are characteristically drier (Douglas and Bliss 1977). In forest environments, soil moisture is often higher in upper horizons because of the transpirational depletion of moisture in lower horizons by tree roots (Knapp and Smith 1981).

2.2.4 Effects of recreational disturbance on soil water availability

As discussed in Chapter 00, impacts on soils by recreational users in wilderness areas can strongly affect soil moisture conditions. The removal of surface litter and soil compaction tends to result in lower infiltration rates and thus lower supply of water to the soil. Loss of surface litter is also likely to lead to higher soil evaporation rates. The loss of upper horizons having more organic matter can also lead to lower moisture retention rates in disturbed soils. Compaction can have the opposite effect, however. Sandy soils that are compacted actually have greater water availability for seedlings than uncompacted ones, because compaction facilitates capillary movement of water in coarse soils, where spaces between soil particles are generally large (Blom 1976).

2.2.5 Assessment of site soil moisture conditions

Determining the moisture status of soils, thus, requires an analysis of general and local climate, topography, soil texture, plant cover, and the kind and degree of disturbance. Since all these factors affect moisture availability to plants, there is no way to predict the relative importance of each factor for each situation. Rather, site specific assessments are necessary. As mentioned above, long term seasonal patterns of precipitation (and their variability) can be obtained for stations nearby. Topography, soil texture, and the nature of soil disturbance descriptions are valuable not only to help determine the site's moisture regime, but also as an important part of a general ecological assessment. Measurement of soil moisture content

through the growing season would be ideal and can be done relatively easily by collecting soils and weighing them before and after drying . At the very least, it is valuable to make a relative evaluation of the seasonal pattern of soil mositure availability (i.e., whether the soil is xeric, mesic, or intermediate). One is then in a better positon to know what plant species to select, the timing of transplants, and the necessity and timing of soil treatments (e.g. mulches, irrigation, incorporation of organic matter).

For example, if the site is an exposed ridge, has thin, rocky soils and is relatively unshaded, drought is likely to be very severe for plants from soon after snowmelt. This site would be considered xeric. In contrast, a forested situation, where soils are deep, rich in organic matter, and shaded, will have relatively higher soil moisture availability. However, drought stress could still be an important factor at this latter site if compaction has reduced infiltration and the litter layer, with its mulching effect, has been lost.

2.3 Soil nutrients: nutrient cycling and nutrient availability

Plants require a large variety of mineral elements, almost all of which are obtained from the soil. Nitrogen, phosphorus, potassium, magnesium, calcium, iron, and sulfur are the elements needed in greatest amounts by plants. With the exception of nitrogen, most of these nutrient elements are present in the soil parent material and are released through weathering. However, it is important to be aware that mineral nutrients are cycled through the soils, plants, and sometimes the atmosphere. Plants take up minerals and then return them to the soil when dead roots and fallen leaves decompose. Some nutrients, such as potassium and calcium, remain in a mineral form and can be taken up again directly once released from decomposing plant materials. Others, like nitrogen and phosphorus, become chemically bound with organic molecules in plants and have to be chemically transformed (i.e., mineralized) before they can be taken up again by plants. Mineralization depends on chemical reactions carried out by soil micro-organisms like fungi and bacteria. The influence of soil microbes in nutrient availability is one of the main reasons that the condition of the soil following disturbance is such a crucial issue.

Although there are detailed protocols set up by soil scientists to determine nutrient deficiencies in soils, these are generally directed at crop and intensively managed timber species and not wild plants. Native species, on the other hand, are generally adapted to less fertile soil (Chapin 1980), and usually do not need the amounts of mineral nutrients prescribed by these analyses. It is important to keep in mind during this discussion of nutrient availability, that an evaluation of soil fertility is relative to individual plant species, and that even among native species there are significant differences in nutrient demand (Grime 1977, Grime 1979). Successful restoration, thus, depends in part on finding the right match of soil conditions and plant species.

Because nutrients have different chemical behavior in the soil, discussion of their availability must be somewhat specific. In addition, some nutrients are more likely to be limiting in disturbed wilderness soils than others. This section will separately cover nitrogen (N), phosphorus (P), and the common soil cations (e.g. potassium (K), calcium (Ca), and magnesium (Mg)). There is also a separate subsection that describes the importance of mycorrhizae fungi in plant nutrient uptake.

2.3.1 Nitrogen

Nitrogen is the element needed in greatest amount by plants and is probably most often the limiting nutrient in soil. Although the earth's atmosphere is around 70% N_2, this form of N cannot be taken up by plants. Nitrogen usually must be in the mineral ammonium (NH_4) or nitrate (NO_3) form before it is available for uptake, although there is some evidence that organic nitrogen can be taken up by mycorrhizae. Because N_2 must first be fixed into NH_4 before it is available for plant uptake, nitrogen from organisms such as nitrogen fixing lichens, blue green algae, or higher plants symbiotic with bacterial nitrogen fixers is an important source of available N in areas undergoing primary succession. The area in front of retreating glaciers and new volcanic deposits are classic examples of places where primary succession occurs. If the N in an ecosystem is not recycled but is lost in ground water or to the atmosphere, its replacement must also come from outside the ecosystem.

The cycling of N is different from most other nutrients in that there are important gas phases. Fixing of atmospheric N_2 into NH_4 begins the cycle (Figure 1). Ammonium can then be taken up by plants and incorporated into organic N-containing molecules such as proteins. Generally, plants that have higher growth rates will have higher N requirements becasue of the need for greater amounts of the protein that converts CO_2 into carbohydrates during photosnythesis. When plants die, this organic N must be broken down by soil microbes into NH_4 for new plant uptake, but it can also be converted to NO_3 by other microbes, an aerobic process called nitrification. Nitrate is much more mobile in soils than ammonium and is readily leached out. Nitrate is also available for conversion by other bacteria to nitrous oxide (N_2O) and N_2, gaseous forms that are then lost to the atmosphere. This conversion, termed denitrification, is an anaerobic process and typically occurs in wet soils. Thus, higher nitrate levels mean more available nitrogen to plants, but also make soils more susceptible to loss of nitrogen.

Nitrogen availability in restoration of disturbed wilderness sites must then be evaluated within the context of this nitrogen cycle. For restoration, crucial points within the cycle are most likely to be the return of plant litter to the soil and the microbial conversion, or mineralization, of litter organic nitrogen into NH_4 and NO_3.

The loss of plant cover from a site due to recreational disturbance results in the loss of an important soil litter source. Consequently, N and other nutrients within the litter no longer are returning to the soil for subsequent uptake by plants. In coniferous forests, understory plants may be a minor amount of the total ecosystem biomass, but they are disproportionatley important as sources of litter nitrogen (Turner and Long 1975). Litter from grasses, forbs, and deciduous shrubs is higher in nitrogen, is being renewed every year, and is more easily broken down compared to litter from evergreen trees. Loss of the O and A horizons as a result of disturbance most likely means a major loss in nitrogen from the site, since most of the nitrogen stock is usually located in these horizons near the surface.

Site disturbance is likely to lower rates of N mineralization, where soil microbes convert organic N to NH_4 and make it available to plants. Although little work has been done to

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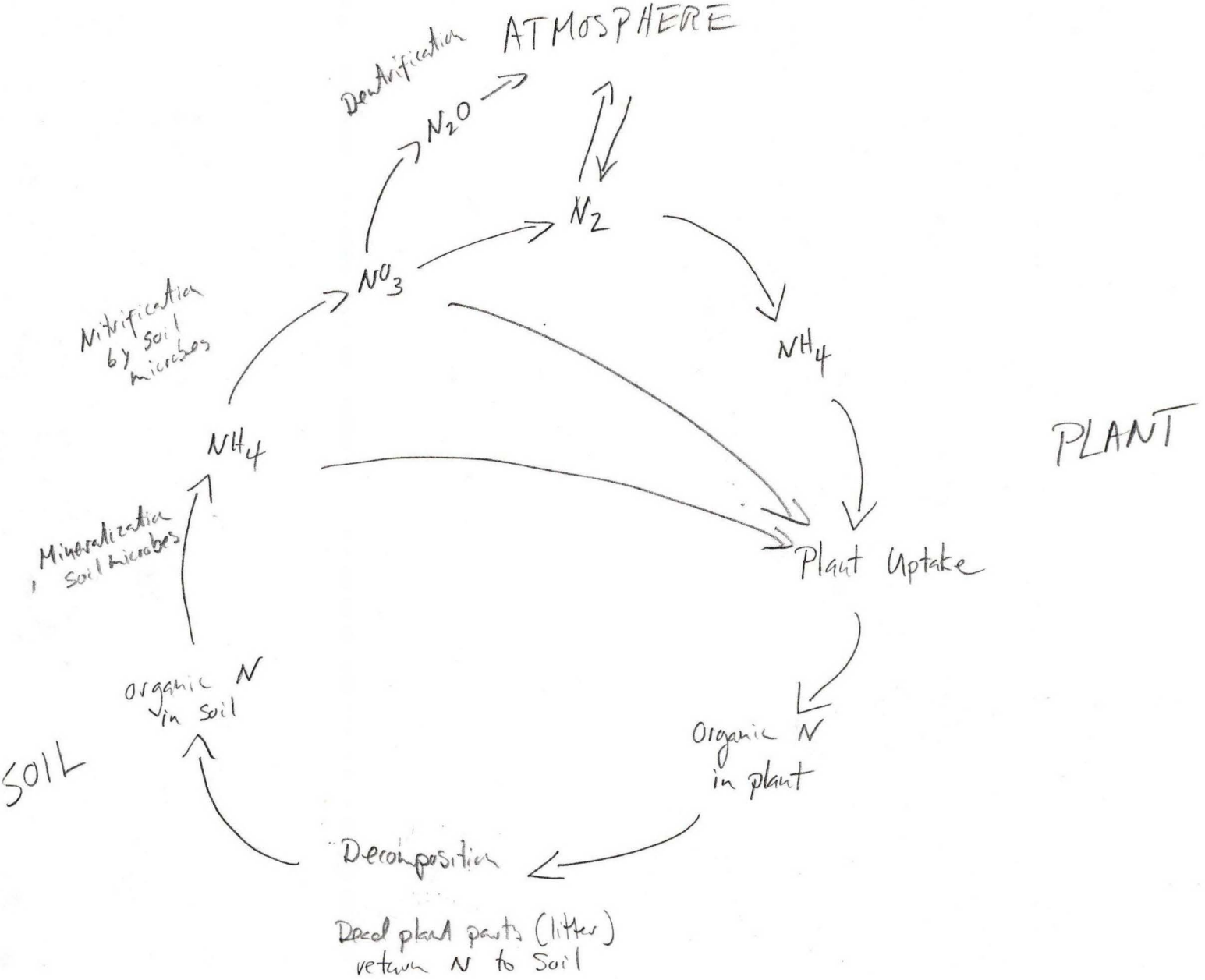

Figure 1. Generalized nitrogen cycle showing forms and transformations of nitrogen in soil, plant, and atmosphere. Important points in cycle for recreationally disturbed soils are the return of litter to soil and the mineralization of organic N to NH_4.

evaluate changes in N mineralization rate in response to recreational disturbance, mineralization rates have been shown to decline when soils are compacted (Whisler et al. 1969 cited in Kuss 1986). The loss of surface litter (i.e. O horizons) as a result of recreational disturbance should also result in reduced mineralization, since that is where most mineralization is taking place (Vitousek et al. 1982).

Denitrification is another potential pathway for N to be lost from disturbed sites. Soil compaction, especially in meadow soils, could lead to greater denitrification rates due to a decrease in soil oxygen levels. The magnitude of these losses is difficult to estimate, since so little work has been done in this area, but any treatments designed to alleviate other effects of compaction will also likely reduce these losses.

Obtaining a complete picture of soil nitrogen availability is not easily done. Analysis of soil NH_4 or NO_3 only gives the amount of these ions in the soil at that particular time. Since plants and microbes are usually taking up NH_4 and NO_3 soon after it becomes available, the amount of these in the soil is not really indicative of the soil's ability to supply N to plants. Total soil N (sometimes referred to as total Kjeldahl N, after the method used to analyze it) is probably a more realistic estimate of the amount of available soil N, but this can also be misleading as organic N is usually its largest component and is not necessarily available to plants. Ideally one wants to know the flux of available N, i.e. how much becomes available over time. Unfortunately, measuring the flux of soil mineral N requires labor and time intensive incubation methods that are not likely to be possible in most restoration efforts. Probably the best compromise to estimating soil N in disturbed wilderness recreation sites is to measure total N, realizing that this is not necessarily a measure of available N because of the disruption of N mineralization processes.

Performing an analysis of total soil N and NH_4 and NO_3 concentration can be done by professional analytical laboratories. Two ounces of soil, air dried and left in a plastic bag is suitable for analysis of total N and $N0_3$, as well as most other soil chemical properties. Soils should be collected from the same depth at several locations and well mixed. Duplicate sub-samples from this composite sample should be analyzed.

The range of total soil N in temperate region mineral soils is around 0.02 to 0.50% (Brady 1974), but in interpreting the results of soil N analysis, it is the relative amount of N in disturbed versus similar undisturbed soils that is most important. If N content from a disturbed site is substantially lower than that in an undisturbed site, say 30% or more, then there should be some concern about nitrogen loss.

Even without chemical analysis, one can reasonably speculate that if the O and upper A horizons of the disturbed soil are gone or severely compacted, there is likely to be much less organic N and flux of available N than in undisturbed situations. Consequently, there is probably a strong need at such a site to provide an organic nitrogen source (i.e. easily decomposable litter) in order to reestablish nitrogen cycling processes. Although the issue of fertilization will be taken up in a later section, it should be clear from this discussion that the addition of nitrogen fertilizer, while it does provide a readily available supply of N to plants, is only a short-term solution to the loss of soil N and of cycling processes that make this N available to plants.

2.3.2 Phosphorus

The cycling of soil phosphorus (P) differs from that of nitrogen in several respects. Unlike N, soil P is derived from minerals in the soil parent material. There is no P gas phase like that of N (i.e. N_2,N_2O), and P consequently can not be lost as a gas from an ecosystem. The concentration of mineral P is much lower in the soil than that of N, and much of the P in soil is in an insoluable form that can not be readily extracted by plants.

As with N, P is cycled through plants and soil, as plants take it up and return it to the soil as organically bound P in litter. Organically bound P is typically about 30-50% of total soil P (Paul and Clark 1989). The mineralization of this organic P is the primary means by which availabile P is replenished in the soil, which means that an active soil biota must be present for this to occur. Soil micro-organisms and plant roots also make available insoluble soil P (e.g. iron, aluminim, calcium phosphates) by the production of CO_2 and organic acids. Because most of the organic P pool is derived from litter and decaying plant roots, the

upper soil horizons are disproportionately important as sources of available P. Similar to the distribution of N in subalpine and alpine soils, the amount of total and available P usually decreases with depth through the soil profile (Douglas and Bliss 1977, Fonda and Bliss 1969, Nimlos and McConnell 1965).

The estimation of P availability in recreationally disturbed soils is subject to the same difficulties as that of estimating available N. Available P is usually measured with a dilute acid or alkaline extraction, which removes most of the P that readily exchanges with the soil solution, but this does not include most organic P. Total P includes available and organic P, but also insoluble P, which is not available to plants. Since none of these measurements is sufficient in itself, perhaps the best strategy for estimating P availability in assessing restoration needs is to measure available P, total P, and organic matter content in disturbed and nearby undisturbed soils. If it is not possible to make these measurement, one can probably assume that P availability has gone down if the surface horizons have been lost. If the surface horizons have been lost and/or if there is severe compaction in the soils, there has also likely been a reduction in soil biological activity. Consequently the cycling of organic P to mineral P will probably be reduced.

As with nitrogen, fertilizing with phosphorus provides a readily available supply of the nutrient in the short-term, but does not reestablish the cycling processes and long-term store of P. This is most effectively done by adding easily decomposible organic matter to the soil and facilitating the development of a new O horizon.

2.3.3 Other Mineral Elements

Plants require numerous other mineral elements besides N and P, such as potassium, calcium, iron, and magnesium. These nutrients do not generally become bound into organic molecules and are released in their mineral form as litter decomposes. Because they are taken up as ions, or charged molecules, the ability of the soil to hold onto these charged molecules is an important factor in overall soil fertility. Sand particles are notably lacking in charged sites to bond to charged mineral ions, which is a major reason for sandy soils

being relatively infertile. Clay and silt particles and organic matter have more abundant charged sites, and soils with a higher proportion of these components retain mineral nutrients very well. Again, the importance of organic matter in soils is evident, particularly in sandy soils. If the upper horizons with most of the soil organic matter is lost, the ability of soils to retain mineral ions will be reduced.

Although soils in wilderness areas may be naturally deficient in one or more mineral nutrients when compared to soils from agricultural or managed forest situations, this should not be viewed negatively from the perspective of restoring disturbed sites. In some cases, site evaluations of disturbed wilderness areas have included a standard agricultural soils analysis, with the result being a recommendation to add the deficient mineral elements. But these recommendations may be inappropriate since native plant species that would normally be found on an undisturbed site have evolved to grow on these soils and do not necessarily have the mineral requirements that crop plants have.

Campsites might be expected to have increased levels of certain nutrients, because campfire ashes are very rich in mineral elements. In addition, leaching has probably decreased due to lower infiltration rates. Actual measurements of levels of these nutrients in recreationally disturbed sites have given variable results, however, with increases (Cole 1982), decreases (Stohlgren 1986), and no changes (Rutherford and Scott 1979) in levels are all reported. Although in some cases, lowered levels of these mineral nutrients may limit plant productivity in disturbed sites, it would seem that they are likely to be much less significant than N and P, which are more closely linked to soil organic matter and litter.

2.3.4 pH

Soil pH is a measure of how acid or alkaline the soil is. Forest, subalpine, and alpine soils in the western U.S. are usually quite acid, with pH commonly in the 3.5 to 5.5 range. Such a low pH is usually considered detrimental from a soil fertility stand point. Many plant species can not tolerate such acidic conditions, and a low pH makes some nutrients, such as phosphorus, less available. However, montane plants are evidently well adapted to a low

pH and in some cases (e.g., Ericaceous species such as *Vaccinium* spp.) even appear to prefer acid soils.

2.3.5 Mycorrhizae

Most plant species have a symbiotic relationship with fungi, in which the fungi become associated with plant roots and transfer nutrients from the soil to the plant. In return, the plant gives up carbohydrates to the fungi for energy. These fungi, termed mycorrhizae, are required by many plant species and are especially important for plant uptake of phosphorus. There are two basic types of mycorrhizae, ecto- and endo-mycorrhizae. Ectomycorrhizae are characteristic of woody plants, including both conifers and angiosperms. The mycelia of ectomycorrhizae form net-like associations around the plant root tips. Ectomycorrhizal spores are typically small and released above ground, facilitating spore dispersal by wind. Endomycorrhizae, also called vesicular-arbuscular mycorrhizae (VAM), are characteristic of herbaceous plant species. They form mycelial associations in the intercellular spaces within plant roots. Spores of endomycorrhizae are larger and released below ground, hindering dispersal to soils lacking in mycorrhizae. Inoculum of endomycorrhizal (either spores or infected roots) have been found to be lacking or much reduced under a variety of disturbed conditions, such as mine tailings, eroded areas, and roadbeds.

There has been little research on effects of recreational disturbance on plant-mycorrhizal associations, but in disturbed wilderness sites where vegetation has been lost, the amount of mycorrhizal inoculum is probably reduced. Loss of top soil or compaction are also likely to reduce infection rates of plants by mycorrhizae (Simmons and Pope 1987).

Evaluating the mycorrhizal status of plants requires specific training and considerable effort and is not feasible for most wilderness restoration projects. Most commonly, endomycorrhizae are the primary concern, since their low spore dispersal reduces their reintroduction to disturbed sites. They also will be important for establishment of herbaceous understory and meadow plant species. Fortunately, it is fairly easy to introduce mycorrhizae to soils if one suspects they are reduced in abundance or lacking. Merely

introducing soil rich in plant roots from a nearby undisturbed site and mixing it in with the disturbed soil makes mycorrhizal spores and mycelia available for infection of plant roots. Alternatively, one can take roots of plants, chop them up, and introduce them to the soil. Matching the plant species and mycorrhizal fungi species is not usually a major concern, since endomycorrhizae are not highly species specific. Ectomycorrhizae, however, tend to be more species specific.

To get mycorrhizae reestablished in a disturbed site, it is also important that soil conditions are conducive to infection of plant roots and growth of the mycorrhizae fungi. Generally, these conditions will be those favorable to growth of plant roots: well aerated soils with good crumb structure and moderate moisture status. Probably what is most detremental to mycorrhizae in recreationally disturbed soils is soil compaction. Consequently, loosening of compacted soils (but not necessarily tilling and turning over the soil) is highly recommended to aid the establishment of mycorrhizal associations with plants used to revegetate the site.

3. PLANT PROCESSES

Reestablishing plants on a disturbed wilderness site is perhaps the most easily conceived goal of a restoration project. Plants, especially native species, are the most important aesthetic component in restoration and are critical to reestablishing natural soil processes that have been disrupted by recreational impacts. Consequently, one must have an understanding of how plants function when selecting appropriate species for reestablishment, deciding how they will be introduced to a site, and how they will be maintained over the long-term. This section is a brief discussion of plant processes that are important to revegetating disturbed sites. Several topics will be addressed, including plant strategies, growth forms, life histories, ecophysiology, and the biology of seeds.

3.1 Plant Strategies

In order to select plant species for revegetation , it is valuable to be able to predict how successful a species will be in becoming established, surviving, and growing on a particular site. Because site characteristics can be so variable and the degree of disturbance will vary, one must make an attempt to match characteristics of perhaps several species with the particular conditions at a site.

One useful model for characterizing plant species has been developed by Grime (1977, 1979), in which he grouped species according to their morphological, life history, and physiological traits. Grime was trying to explain why plants often showed particular combinations of traits, which he called "strategies", and why plants may have evolved to develop such strategies. In addition to its theoretical value, Grimes's idea of plant strategies has practical utility in offering a simple, yet informative way to categorize plants according to their ecological roles. Knowing a plant's strategy can tell us a great deal about how appropirate it will be in a revegetation plan.

Grime identified three basic plant strategies: ruderal, competitor, and stress tolerant. Species that employ each strategy have evolved and are generally found in habitats that vary

in frequency of disturbance and in degree of stress (where stress is defined as constraints on plant productivity, such as drought, low nutrients, cold temperatures, and toxins). Environments with a low degree of stress but a high frequency of disturbance are generally dominated by ruderal species, typified by fast growing species with high seed output such as annuals and crop plants. Competitors are commonly found in low stress (i.e. productive), low disturbance communities, and have characteristics tending toward large stature, moderately high growth rates, and long life-spans. Stress-tolerators are found typically in high stress environments (i.e having low resource levels and/or subject to extreme environmental conditions) that have low disturbance frequency; they generally are smaller, have slow growth rates, and low demand for mineral nutrients and water. No viable strategy is found in environments with both high stress and high disturbance frequency.

Since subalpine and alpine conditions commonly found in wilderness areas represent the upper end of a stress gradient relative to lowland environments (i.e, low temperatures, short growing season, often low nutrients), repeated disturbance to such sites may result in a situation falling under the "no viable strategy" category in Grime's scheme. The efforts by wilderness managers to restrict visitor use from newly revegetated areas are, thus, well justified and are critical to the success of any restoration program in relatively stressful environments.

Although developed as a means of explaining differences among vegetation types, this model can also be used at smaller scales. For example, while alpine and subalpine herbaceous species are "stress-tolerant" relative to lowland annuals, there can be important differences among the strategies of different alpine species. Such differences have been used to predict the resistance of species to disturbance in wilderness areas (del Moral 1979). Although not placing them within Grime's model, Chambers et al. (1987) found clear differences in plant characteristics between early (e.g. *Deschampsia cespitosa*) and late (e.g. *Geum rossi*) successional alpine species from the Beartooth Mountains, Montana that suggest, respectively, ruderal and competitor strategies. The ruderal species had smaller seeds that were more easily dispersed, had a higher growth rate, and higher nutrient demand. Accordingly, it was a more common colonizer in disturbed sites. Also illustrating differences

in strategy among alpine species, Roach and Marchand (1984) found some species in the Appalachian alpine to have distinctly ruderal characteristics (e.g. *Arenaria groenlandica* and *Juncus trifida*) compared to other species from the same flora (e.g. *Potentilla tridentata*). The ruderal species were more likely to colonize barren areas created by recreational disturbance than other species.

This variability within a flora can be utilized by revegetation workers to select species appropriate to given site conditions and revegetation goals. For example, if relatively fast growing species are desired (e.g. ruderal or competitor strategies), a plant will tend to require high levels of nutrients and water; and, thus, site conditions will have to be relatively favorable. If site conditions are unfavorable and can not be ameliorated, competitors or ruderals are not likely to grow or even survive, and a more stress-tolerant species would be appropriate.

The main drawback in using this model of plant strategies is a lack of data on individual species, which makes it difficult to categorize them according to strategy. However, a number of readily observable indicators exist that can be used to make reasonable estimates of plant strategy type. Ruderal species are likely to be found in disturbed areas, such as trail and road cuts, wells from fallen trees, or areas of soil instability. Stress tolerant species are found in xeric areas or places with rocky, thin soils. However, ruderal or stress tolerant species may occur in low densities in stable communities dominated by one or two competitor species. Fast growing competitor species are often rhizomatous or stoloniferous, two characteristics that are easily identified and facilitate spreading of individuals on bare surfaces. While Grime's model is a generalization of many plant characteristics, it is also useful to consider life history, morphological, and physiological characteristics separately.

3.2 Reproductive Characteristics

Life history characteristics are those that determine the ontogenetic development, reproduction, and life span of organisms. Of these characteristics, those pertaining to reproduction are the most important to restoration of disturbed sites. Ruderal species

typically have high numbers of offspring, which promotes spread of populations and colonization of disturbed sites. As previously mentioned, species with high seed output can be important natural colonizers in subalpine and alpine environments. The occurrence of ruderal type species in these high elevation habitats, however, is relatively low compared to lowland areas, which is one of the main reasons problems with weedy species are not common in disturbed montane wilderness areas. Consequently, natural colonization of disturbed sites is much slower and other sources of plant cover are usually needed.

Another aspect of plant reproductive biology that has a great deal of importance for revegetation work is sexual versus asexual reproduction. Sexual reproduction in flowering plants means that seed must be produced. Seed output is often limited in alpine and arctic plants because of short growing seasons and generally low levels of plant productivity and is thus likely to constrain growth of plant populations in these environments. In addition, sexual reproduction requires successful seed germination and seedling establishment, which are often reduced in high altitude habitats.

Asexual reproduction can be accomplished by a variety of means, but the most relevant to revegetation is that of clonal production of individual plants. Plants that spread by rhizomes or stolons (aboveground runners) in effect produce numerous potentially autonomous individuals (ramets) that can lead to relatively rapid increases in plant cover. Connections between ramets allow for the transfer of resources from established to newly produced ramets, which can be crucial for the survival of ramets spreading into more stressful habitats like that of an impacted campsite. Common rhizomatous or stoloniferous plants in western mountains that have shown high potential for revegetation work include luetkea or partridge foot (*Luetkea pectinata*), twin-flower (*Linnea borealis*), and sibbaldia (*Sibbaldia procumbens*). Others that have not been previously used but that may be valuable include wild strawberry (*Fragaria* spp.) and vanilla flower (*Achlys triphylla*). Many grasses and sedges have tillers, which are functionally equivalent to rhizomes, and offer high potential for spreading into barren areas. Stoloniferous plants may be more successful than rhizomatous ones in disturbed sites, since their means of spreading is aboveground, reducing the constraints on belowground growth imposed by soil compaction. The advantages of asexual reproduction

are well recognized in revegetation work, but the number of asexually spreading species examined for actual use is very limited and definitely needs to be expanded.

3.3 Morphological Characteristics

3.3.1 Shoot and leaf morphology

Higher plants can be roughly divided into those with woody shoots (trees and shrubs) and those with herbaceous shoots (forbs and graminoids). Woody structures confer such advantages as a maintenance of canopy height and resistance to mechanical damage, but costs include less allocation to photosynthetic leaf area and slower relative growth rate (Bliss 1985). Once damaged they are also slower to recover, unless they can send up new shoots from roots (Cole 1988). Because of their slow relative growth rates, the choice of subalpine or forest woody species in restoration work is likely to require the use of transplants. Woody species tend to have lower root:shoot ratios, however, compared to herbaceous species (Bliss 1985), and loss of what seems to be a small amount of root biomass during transplanting can have significant effects on water and nutrient uptake and, thus, survivability. Because of slower growth and higher susceptibility to mortality after transplanting, use of woody species in revegetating subalpine and alpine areas is likely to be less successful than use of herbaceous species.

Phenology is one important component of leaf morphology and can be represented as a continuum from evergreen leaves to deciduous leaves (which also includes most herbaceous plants). Because a variety of other morphological and physiological characteristics are typically associated with either evergreenness or deciduousness, these two types of leaves can serve as useful indicators in selection of species. Evergreen leaves have been shown to have higher nutrient use efficiency (Gray 1983) and usually have higher resistance to water loss than deciduous leaves (Schlesinger and Chabot 1977). In addition, they are well adapted to short growing seasons because their photosynthetic apparatus is already in place immediately after snowmelt, although deciduous shrubs from subalpine and alpine environments can also tolerate short growing seasons if they have high storage capacity in

roots or woody stems. Evergreen leaves, however, tend to have lower photosynthetic capacity compared to deciduous leaves, resulting in lower relative growth rates. Because they entail greater investment in carbon to construct compared to deciduous leaves (Merino et al. 1982), loss of evergreen leaves due to drought, frost-damage, herbivory, or recreational impact constitutes a greater cost to a plant. Wintergreen leaves are an intermediate form of leaf phenology between evergreen and deciduousness, where leaves are retained over only one winter, and can be expected to have characteristics intermediate between the two extremes (Bell and Bliss 1977). Phenology is thus one indicator of general stress tolerance, with species having evergreen leaves usually being more stress tolerant than those of similar growth form having deciduous leaves.

It would appear from the above discussion of shoot and leaf characteristics that herbaceous species are likely to be more successful as transplants in revegetation programs than woody species and that among shrubs and trees, deciduous are preferable over evergreen species. This general recommendation is no doubt subject to exceptions.

3.3.2 Rooting pattern

Morphology of plant belowground structures also needs to be considered in selecting species, getting plants established, and determining maintenance requirements for revegetation of disturbed sites. Rooting pattern has a major effect on how a plant is adapted to different soil conditions and how suitable a species is likely to be for transplanting. Plants with high root:shoot ratios (i.e., considerably more than half the plant biomass being root) can extract more soil water and mineral nutrients per unit leaf area than plants with lower ratios, and environments with low levels of water and/or nutrients tend to have plants with high root:shoot ratios (Chapin and Shaver 1985). Thus, if a disturbed site has low nutrient or moisture levels, species having high root:shoot ratios are likely to be more successful relative to those with low ratios.

Unfortunately, the only way to determine root:shoot rateios and rooting pattern is to dig the plant up, although there are some root:shoot data in the literature (e.g., Antos and Zobel

1984, Oberbauer and Billings 1981, Kuramoto and Bliss 1970). To lessen the disturbance from digging up plants to examine root characteristics, plants in construction areas such as rerouted trails, new campsites, and borrow areas can be carefully excavated. Excavation of isolated plants is also relatively low in impact. As with examining soils, it is valuable to look belowground in order to become familiar with a portion of the plant that is not normally observed but is just as important as leaves and shrubs.

In considering the relationship between root:shoot ratios and resource availability, it is important to distinguish between roots used as storage organs and those used for resource aquisition. Large storage roots obviously confer different advantages to plants than spreading root systems, and theyshould be distinguished from tap root systems whose primary function is to reach deeper soil depths. Although not used for revegetation purposes, transplants of *Polygonum newberryi*, a subalpine herb from the Cascade Mountains with very thick storage roots, were more successful than those of *Eriogonum pyrolifolium*, a co-occurring species with a spreading root system (D. Chapin, unpublished data). The large storage reserves in protected belowground structures appear to be a characteristic that confers a high capability for transplanting. In contrast, tap root systems that have less storage function but penetrate deeper soil depths are less suitable for transplants, because it is so difficult to extract the root system. One study (May et al. 1982) showed that fibrous rooted plants did better as transplants than plants with spreading root systems, which in turn were more suitable as transplants than tap rooted plants.

3.4 Physiological characteristics

A number of physiological characteristics have been mentioned already in the context of life history and morphological traits. Other physiological attributes of plants that are likely to be important to selection of species for restoration work include characteristics pertaining to requirements for light, moisture, temperature, and nutrients -- the abiotic factors that largely govern the distribution of plant species. While a complete review of plant ecophysiology is not in order, it is worthwhile to briefly discuss a few critical traits.

It is obvious that species adapted to high light environments are not likely to do as well in shady habitats. If the photosynthetic saturation point of a plant is at 75% of full sun, growth in a shady site where light levels might average 10% of full sun is going to be light limited. This, however, does not necessarily exclude the use of high light species in low light environments in revegetating a site. Disturbed sites have greatly reduced levels of plant competition, and plant species from high light environments can often acclimate to low light conditions (Boardman 1977). It is more likely that a shade tolerant species will not be successful in a sunny environment. Such species often have little resistance to water loss because of thin leaf cuticles and lower stomatal resistance and consequently are more sensitive to the higher evaporative demand in sunny habitats (Smith 1985).

The ability of plants to survive drought stress is due to various combinations of drought avoidance and drought tolerance. Because drought stress is likely to exert a major influence on the success of colonizing plants in revegetated sites (whether seedlings or transplants), the ability to avoid or tolerate drought is often an important criterion in the selection of species. Characteristics of plants that are able to avoid drought are usually morphological. These include high leaf resistance to water loss (thick cuticles, small leaves, fewer stomata and distribution of stomata on lower leaf surfaces only), a high proportion of root to leaf surface area, deep roots, and the ability to drop leaves during times of drought stress. Physiological drought tolerance is primarily the result of the ability to develop high concentrations of solutes in leaf tissues and is thus not readily observable without specialized equipment, such as a Scholander Pressure Chamber. There are relatively few species whose ability to tolerate drought has been evaluated, making selection of species on the basis of drought tolerance difficult.

The ability to grow at relatively low temperatures and to tolerate freezing conditions during the growing season are two characteristics that subalpine and alpine plants must have to survive at high elevations. The lack of these two characteristics is probably one of the major reasons introduced species are poor choices for use in high altitude revegetation programs.

The ability to tolerate high temperatures can also be important for survival of subalpine and

alpine species, especially as seedlings. Because surface temperatures in open subalpine sites can sometimes exceed 50°C, heat stress can be a major source of seedling mortality, an important consideration in revegetating subalpine or alpine meadows or fell fields. For example, seedlings of two subalpine lupine species from the Cascade Mountains were found to have very different tolerances of high temperatures (Braatne 1989). *Lupinus lepidus*, a prostrate species found in open sites, had a much higher optimum temperature for photosynthesis and higher seedling survivorship during periods of high temperature than did *Lupinus latifolius*, an erect species more typical of the forest understory.

Plant nutrient requirements are another important factor in selecting species and implementing a successful revegetation program. Although it is unclear to what extent recreationally disturbed sites in wilderness areas differ in soil nutrients from undisturbed sites, subalpine and alpine soils are typically much less fertile than lowland soils. As a result, species native to these habitats are more tolerant of low nutrient levels and commonly have slow growth rates, opportunistic uptake of nutrients, and well-developed mechanisms of nutrient retention. This is not to say, however, that loss of soil nutrients from disturbance is not detremental. Clearly, loss of nutrients is very critical in soils where nutrient levels are already low. Plants adapted to low soil nutrient levels can benefit from higher nutrient levels, and subalpine and alpine plants often have higher productivity when fertilized, especially when nitrogen is added.

3.4 Seed Biology

Seeds play a fundamental role in the life history of a plant because they are important as propagules for plants to move locally or across the landscape and because they initiate the most vulnerable time of a plant's life. Thus, the seed characteristics of a species are determinants of where and how a plant becomes established, which is obviously a major factor in restoring disturbed sites.

Seed size is one of the most critical characteristics affecting both dispersibility and survival of germinants. A site just a few meters away from potential seed sources may receive very

few seeds if those source plants have large seeds that are not wind dispersed (del Moral and Wood 1987). On the other hand, large seeds confer a greater ability for seedlings to survive drought and competition (Baker 1972, Harper et al. 1970). In an alpine revegetation project in Alberta, for example, large-seeded grass species were found to have greater survival than small seeded species (Walker 1982). Since dispersal of seeds in restoration can be human assisted, the selection of species for seeding should probably be toward large seeded species, all other characteristics being equal.

Seed germination requirements vary among species. Light, temperature, moisture content, and scarification (breaking the seed coat) have all been found to affect germination rates (USDA 1978). Generally, if seeds are sown so that they experience conditions similar to those of naturally dispersed seeds, germination requirements will probably be met and will not need to be determined experimentally. Seeds sown in the fall, mixed in with the surface soil, and in a habitat where that species is likely to be found will probably not require special treatment for germination. They will have experienced a cold treatment often necessary in montane species, will have imbibed water from melting snow and moist soils in the spring, and will be exposed to a natural light regime.

Successful seed germination and seedling survival has been found to be well correlated to the presence of "safe sites" (Harper 1977). Safe sites typically include small crevices in the soil surface, the edges of small rocks or pieces of wood, and the shade of larger plants when conditions are sunny. These sites provide amelioration of environmental stress (usually drought or temperature) at a scale of millimeters to centimeters, allowing greater probability of survivorship for a germinating seed. A heterogenous soil surface and one littered with rocks or small logs is likely to have more numerous "safe sites" than a smooth surface, another reason to break up a compacted soil surface.

The longevity of seeds affects how long they can remain viable in the soil. Seeds that remain viable for two to several years in the soil can accumulate in a soil seed bank, making the soil itself a good source of seeds (Gartner et al. 1983). However, soils that have been disturbed for longer periods will likely have poor seed banks. Longevity also affects the

ability of seeds to survive storage. Chambers (1989), for example, found that early seral alpine species had longer lived seeds than late seral species and consequently could be stored longer.

4. PLANT COMMUNITY DYNAMICS

Since plants rarely occur alone, interactions among plants of the same or of different species occur in all plant communities. These interactions can occur in a variety of forms, including competition for resources, allelopathic interference, and amelioration of environmental stress (the nurse plant phenomenon). Because disturbance alters plant communities by destruction of individuals and changes in soil conditions, these interactions are likely to be different in disturbed versus undisturbed sites. Succession and competition are two types of interactions among plants that have direct bearing on restoration.

4.1 Succession

It is difficult to place the restoration of disturbed sites into the usual framework of primary versus secondary succession, as it has characteristics of both. It resembles secondary succession in the sense of a previous plant community reestablishing itself; but when soil conditions have deteriorated in soils that are already poorly developed, the circumstances are similar to those that occur under primary succession, when species invade newly deposited substrates (e.g. volcanic deposits, mine tailings, areas exposed by glacial retreat). As the intensity of disturbance increases, the initial role of biological component in an ecosystem decrease in importance, and physical components become more important (DePuit and Redente 1988).

At higher elevations the slowness of successional processes and the potential variability in successional pathways makes prediction of successional change following disturbance difficult and possibly moot. Frank and del Moral (1986), for example, found that 35 years of succession on a disturbed subalpine site on Mount Rainier in Washington state did not result in a community similar to nearby undisturbed areas. Roxburgh et al. (1988) found similar results in succession after disturbance at an alpine site in New Zealand. Restoration workers should, therefor, not expect to duplicate natural successional processes or follow some predictive model of successional change, although some would probably disagree with this opinion (e.g. Marchand 1980). The value of successional theory to restoration is likely

to be greater as a source of insight into creating effective techniques than as a specific model to follow.

Connell and Slatyer (1977) outlined three mechanisms of succession: facilitation, tolerance, and inhibition. Each of these mechanisms pertains to different types of plant-plant interactions that may occur in the the course of succession. Facilitation refers to the positive effects one species may have in preparing the environment for species coming in later seral stages; inhibition, on the other hand, refers to ways that one species might retard species that come in later; and tolerance is the persistence of species until resource levels drop to permit the invasion of more tolerant species. The facilitation model is likely to be most pertinent to succession on severly disturbed sites in wilderness areas, where interference by other species is not likely to be as important as abiotic stress. The question then becomes how facilitation might be encouraged on a site to make it more conducive to survival and growth of introduced or naturally invading plants.

Establishing a plant cover to hold soil, contribute organic matter, and retain nutrients is an example of such a facilitative interaction of plant species. Some success with this idea has been shown in at least two attempts in higher elevation sites (Ketchledge et al. 1985, Keigley 1989). Although neither of these two studies used native species to establish an initial plant cover, the use of annual grasses or grasses that required higher temperatures or nutrients for the cover crop resulted in (1) amelioration of growing conditions, (2) mortality of the "facilitator", and (3) natural colonization by native species. Because of mortality of the cover crop species, concerns about using a non-native species were alleviated. Another example of facilitation that might be tried in a very exposed site is to transplant shrubs that shade seeded areas. The use of nitrogen fixers, such as lupines, in restoration projects should also lead to facilitation through the addition of nitrogen to the soils.

4.2 Competition

Competition involves the interference of one plant by another, usually by uptake of light,

nutrients, or water and making them unavailable for use by other plants. Competition is usually considered most intense in productive, stable environments as opposed to stressful or disturbed environments, presumably because more species are able to become established and plant densities are usually high. However, competitive effects have been shown to occur in desert environments where plant densities are low (Phillips and MacMahon 1981, Fonteyn and Mahall 1978).

Competition is not likely to be of major importance in restoring disturbed sites in mountainous wilderness areas, at least at first. Since these sites are usually stressful environments, plant densities are usually low and competitive interactions will probably be minimal. In sites where disturbance intensity has not been high or in more productive environments, competition has been shown to be a factor in restoration. In these cases, competitive dominance by one species may hinder establishment or growth of a more desired species. For example, Everett et al. (1980) found that grass competition generally reduced shrub survival in the revegetation of mine tailings in the Sierra Nevada of California; and in Great Britain, seedlings of herbaceous species lowered success of birch seedlings in revegetation of roadsides (Buckley 1984). At lower elevations, competition by weeds can be a major problem, and can reduce survivorship of seedlings and transplants (Van Epps and McKell 1983).

Where competition is a problem in site restoration, the use of a dense plant cover (or, in horticultural terms, a cover crop) is one way to reduce invasion by undesirable species without resort to herbicides. Such a cover crop could be an annual species or could be selected to last for a longer period. It could be used to establish a dense cover in the area between transplants or could itself be the species assemblage selected for revegetating a site. Thus, cover crops are an agronomic tool that can be designed to fill specific ecological roles. As mentioned previously, another role is that of a "facilitator" to make a site more suitable for colonization. Thus, which ecological role a cover crop fills will be specific to the site and the restoration plan.

One of the results of disturbance is to reduce competition, thus opening up a site to

establishment by plants that would normally be excluded. Often these species are suppressed by more competitive species and consequently are found in only small amounts within a plant community. For example, in arctic heath and tundra communities of Scandanavia, species found in exposed windswept sites invaded disturbed heath where they were normally not found (Muller 1952). And in another example, disturbance in subalpine meadows of the Olympic Mountains, Washington resulted in the expansion of some suppressed species (del Moral 1985). Examining naturally disturbed sites, such as uprooted trees or rodent burrows, is one way of identifying such species in an area for potential use as colonizers of recreationally disturbed sites.

5. ECOLOGICAL ASPECTS OF RESTORATION METHODS

Site restoration in wilderness areas is at the interface between horticulture (traditionally developed for intensively managed ecosystems) and ecology (the study of largely natural ecosystems). Consequently, there is a need to examine horticultural methods from an ecological perspective. In one sense, that has been the subject of this entire chapter, but it is also useful to discuss specifically several commonly used techniques and their ecological implications.

5.1 Scarification

Tilling of the soil on a disturbed site, commonly called scarification, is widely practiced as a means of loosening up compacted soils. Soil compaction is a major problem on recreationally disturbed sites that has a wide variety of effects including lower rates of root growth, mycorrhizal infection, and infiltration. When such conditions exist, it would seem imperative to loosen the soil manually. However, there are sometimes good reasons not to scarify the soil, and how scarification is carried out can be important.

Scarification results in major alteration of soil structure. When soil structure has already been disrupted by compaction, scarification can be beneficial: it increases infiltration, reduces potential resistance to root growth, increases pore size and volume, potentially increases soil aeration, and creates surface heterogeneity. However if the soil retains a favorable crumb structure, scarification can break down that structure and be detrimental to plant growth. Consequently, it is important to determine the degree of compaction before scarification is used on a site. For example, even when the centers of campsites have very compacted soils, the margins are less affected and may not need scarification (Stohlgren 1986).

If scarification is done by turning over the soil, existing soil horizons will be mixed, with resulting destruction of any remaining litter layer and A horizons. If a previously buried A

horizon is exposed to the surface, there can be a loss of organic matter as a result of greater oxidation rate. Thus, loosening of the soil rather than turning it over should be the method used, which would tend to preserve any existing horizon development in the soil.

In a study on campsites with compacted soils in Texas, scarification alone was not effective in reducing compaction, but scarification combined with digging in bark and chips and planting of grass did ameliorate the effects of compaction (Legg et al. 1980). One of the secondary benefits of scarification, is more surface heterogeneity, which should increase trapping of seeds and litter and provide more numerous safe-sites for seed germination. Even loosening of the soil, without turning it over, should result in increased surface heterogeneity.

5.2 Mulching

Mulching reduces the loss of soil moisture by absorbing solar radiation and thereby lowering evapotranspiration rates. It also absorbs rainfall, protects the soil surface from the impact of raindrops, and increases infiltration rates. In addition, mulches can increase trapping of seeds, protect young seedlings from temperature extremes, and suppress weeds. Despite all these advantages, the success of mulching in restoration of disturbed wilderness sites has been mixed. In some cases, mulches have been found to increase seedling emergence (Chambers et al., 1990; Dalle-Molle, 1978) or be generally beneficial (Tunison, 1979). In other cases, mulches have resulted in negative effects (Kidd and Haupt, 1968); Smith, 1979; and Walker, 1982) or no effect (Richardson and Farmer, 1981; Smith, no date).

The reason often cited for lack of success with mulches is reduction in soil temperature, which can be a serious problem at high elevations where soil temperatures are low and the growing season is short. The thicker the mulch the more likely soil temperatures will be lowered. Mulches are also ineffective if they blow away, which often occurs with straw mulches.

From an ecological perspective, native hay would seem to be the most desirable type of

mulch for restoration in wilderness areas. It is readily available in backcountry areas and can be acquired without long-lasting damage to natural vegetation merely by harvesting standing herbaceous material from a nearby area toward the end of the season. It is high in nutrients, contains native seed and lacks exotic seed, and provides just the kind of material that naturally contributes to a litter layer. The use of finely shredded wood encased in decomposable netting (e.g., Excelsior netting) has been used widely in revegetation programs and has been effectively used in restoration of disturbed recreational sites. Although it does not offer the nutritional benefits of native hay and is very conspicuous, it does stay in place if nailed down and offers most of the benefits of a mulch listed above. The use of bark or chips is less desirable and can be detrimental because they do not decompose easily, can result in decreased nitrogen levels (because microorganisms need to take up more nitrogen to break them down), do not look natural in wilderness environments, and require more effort in transportation. Straw is difficult to hold in place, amy contain exotic seed, and also has aesthetic drawbacks.

Mulches should be seen as surrogates for a natural litter layer and be designed to fill many of the roles that natural litter does in an ecosystem. Surface litter is more than just dead plant parts; it is a complex of organic strata that have different properties and functions. Recently dead and undecomposed plant parts on the surface are underlain by partially decomposed organic material, which in turn grades into the highly organic A1 horizon of mineral soil. At high elevations, snow creates a mat of litter and helps to cement it together. Mulches can be designed to recreate this complex to replace the important structural and functional elements of a natural soil surface.

5.3 Fertilizing

As with scarification and mulching, there is disagreement about the need for and benefits of fertilizers in restoring disturbed sites in wilderness areas. There are several probable reasons for this lack of concensus, including differences in soil nutrient levels among sites, the presence of more critical limiting factors (e.g., water), and lack of good experimental or measurement methods. When adequate amounts of other resources are available,

appropriate levels of fertilization should result in greater initial growth of seedlings or transplants. This kind of response is attractive to restoration workers because results are clearly evident and usually immediate. This is often only a short term response, however, unless fertilization is repeated indefinitely. Raising nutrient levels artificially requires a management program to maintain the positive effects. The remoteness of backcountry areas and the usually limited availability of labor can make repeated fertilization impractical.

There are also good ecological reasons to minimize or avoid the use of fertilizers in wilderness restoration. Plants growing at high elevations generally have lower nutrient requirements compared to lowland plants from more fertile sites (Chapin 1980). Introducing a pulse of nutrients with an accompanying growth response can be deleterious to a plant in a nutrient poor environment, since increased growth has also increased its requirements for other resources, such as water, and increased its nutrient demand after the pulse has ended. Fertilization may also increase the chances or intensity of herbivory, as high nitrogen levels make leaves more palatible to animals.

An approach that makes more ecological sense is to re-establish the soil microbial populations and the associated nutrient cycling patterns that are characteristic of undisturbed conditions at the site. If the litter layer and upper mineral horizons are missing, nutrient cycling processes will remain disrupted and the soil will have limited ability to retain nutrients and transform unavailable nutrients into forms that plants can take up. Fertilizing is known to retard the development of these processes, such as the establishment of mycorrhizal association.

If fertilizers are used, there are ways to reduce the amount that is applied and the need to refertilize. This can be done by establishing a thick cover of seeded grasses that will take up the nutrients and retain them in roots and shoots (Keigley 1989). Nutrients retained in the dead plant parts can then be released through decomposition and be taken up by soil microbes. If natural hay is added with fertilizers, it provides an energy source for soil microbes, which can then take up nutrients as they process the applied organic matter. Soil microbes are one form in which nutrients are stored during their cycling through plants and

soil. If populations of soil microorganisms in a disturbed site are suspected of being in reduced abundance, top soil from undisturbed sites can be added to introduce or increase their numbers.

5.4 Selection of Species

The choice of which plant species to use is obviously one of the major decision in a restoration project. Using native versus introduced species is one of the first questions that needs to be addressed in regard to species selection (Marion et al. 1986). In the past, revegetation and reclamation methods have mostly been centered on seed mixes, often fairly standard ones, that are composed of wide-ranging and often introduced species. In the past 20 years, there has been a movement to utilize native species, especially ecotypes that are specifically adapted to the conditions of the intended site. From an ethical, aesthetic, and ecological perspective, native species are almost invariably preferred for site restoration in wilderness areas, and it is difficult to justify the use of introduced species.

The use of native species for restoration in montane wilderness areas also has practical advantages, because when properly selected they are much more likely to survive in the soil and climatic conditions found at higher elevations. Compared to most commercial seed mixes, native montane species will likely have lower nutrient demand, be more frost tolerant, and be adapted to a shorter growing season. There are native plant nurseries that now specialize in collecting and supplying seed and transplants of native species, particularly ecotypes adapted to specific areas and site conditions. These nurseries can be utilized as a source of either plant material or advice for the use of native plant species in restoration work.

The choice between native and introduced species is, however, not necessarily clear-cut. One alternative is to consider species that are fairly wide-ranging and occur primarily as colonizers in disturbed areas, but which may not be present in the flora immediately around the site. For example, fireweed (*Epilobium angustifolium*), yarrow (*Achillea millefolium*, and pearly everlasting (*Anaphalis margarataceae*) are plant species native to the Western United

States and have ecotypes that are tolerant of montane environments. They have many characteristics that make them ideal for site restoration, and they are likely to be very successful colonizers on disturbed sites up to subalpine elevations. To use them, however, may require importing seed and establishing populations in an area where they do not already occur. This may be counter to some land management policies regarding the use of exotic genetic material (Keigley 1988).

The choice of which species to use is a technically difficult one and has to be site specific. Much of this chapter has been devoted to describing what characteristics of plants to consider when selecting species appropriate for given conditions. In sum, these plant characteristics to consider include:

- overall plant strategy - competitive, ruderal, or stress tolerant;
- plant morphology - herbacious vs. woody, evergreen vs. deciduous, rooting pattern;
- physiology - nutrient and water requirements, sun or shade plants; and
- seed size - large seeds with lots of reserves vs. small easily dispersed seeds.

Site characteristics to consider include nutrient levels, water availability, and level of shading. A knowledge of the local flora is helpful, but on-site investigations are most important. Generally, one is interested in species that are good colonizers or stress tolerators.

6. CONCLUSIONS: USING AN ECOLOGICAL APPROACH IN WILDERNESS RESTORATION

Since an ecological approach to restoration implies a holistic consideration of the problem, no one aspect of ecosystem recovery can be addressed alone. But applying such an ecological approach necessitates an evaluation of what factors may be affecting restoration success and a capability to determine which are most important in any given situation. What is presented here is primarily an overview and can not be considered a prescription of action. It is best utilized as a framework for assessing restoration needs in conjunction with known, or perhaps newly devised, horticultural techniques. Ecological principles offer guidelines that will give a restoration worker some rationale for making decisions in planning and carrying out site restoration in wilderness areas. An active awareness of the abiotic and biotic environment in which a site exists is essential to understanding what will work in restoring that site and in developing creative and perhaps novel restoration techniques. An ecological approach in wilderness restoration combined with the experience that exists and that is accumulating in the field, should help to refine currently used methods and to direct future research.

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